Comparison between Equivalent Charge Model and Equivalent Dipole Model on Realistic Head Model

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Abstract—Equivalent source layer (ESL) imaging is an important kind of high-resolution electroencephalogram (EEG) imaging. It consists of two categories: equivalent dipole layer (EDL) and equivalent charge layer (ECL). Both of them are assumed to be located on or near the cortical surface and have been proposed as high-resolution imaging modalities or as intermediate steps to estimate the epicortical potential. Here, EDL and ECL based on a realistic head model are presented, both simulations and real data experiment are done to compare these two models. The results show that ECL can provide higher spatial resolution about source location than EDL does.

Index Terms—Equivalent charge layer, equivalent dipole layer, realistic head model.

1. Introduction

As an important technique of high-resolution electroencephalogram (EEG) imaging, equivalent source layer (ESL) imaging, which consists of equivalent dipole layer (EDL) and equivalent charge layer (ECL), was well developed. The rationale for ESL imaging is based on the fact that the scalp EEG is mainly generated by cortical sources. Therefore, by approximating cortical sources or near cortical sources using a current dipole layer normally oriented with respect to EDL, or by approximating cortical sources using ECL, what may be obtained is a fairly good approximation of brain electrical activity as observed from non-invasive scalp EEG [1]. EDL and ECL have been tested as both an intermediate step to get cortical potential imaging [2] and an imaging quantity directly on spherical head model [3]. The equivalent physical models of these two ESL show that the strength of EDL is proportional to the surface potential of the layer when the outside of the layer is filled with an insulator and the strength of ECL is the normal current of the layer when the outside is filled with a perfect conductor. These results provide the theoretical basis of ESL applications in high-resolution EEG mapping [1][5].

Previous studies show that a distributed ECL model may provide a higher spatial resolution than a distributed EDL model does in spherical model. In this paper, we apply those two ESL imaging methods to a realistic head model [6], and compare EDL and ECL by simulations with both dipole sources and charge sources located in subcortical regions. Furthermore, EDL and ECL is compared with data from inhibition of return (IOR) experiment.

The algorithm is outlined in Section 2 and simulations with different charge and dipole sources located within ESL are investigated in Section 3. Then IOR experiment and comparison of EDL and ECL with real ERP data are presented in Section 4. In Section 5, conclusions and discussions are presented.

2. Methods

In this study a three-layer realistic head model is used [6]. The outer layer is the scalp, the intermediate one is the skull, and the inner one is the brain while the conductivities are 1.0 (brain and scalp) and 0.0667=1/15 (skull) [7][8]. There are 1,514, 605 and 1,219 nodes and 3,024, 1,206 and 2,324 triangles in each layer of the realistic model from outer layer to inner layer, respectively. An assumed ESL is constructed by contracting the brain layer to 87.5% of its size. A current dipole layer with 2,674 radial dipoles for EDL or a charge layer with 2,674 charge pairs distributing on the surface for ECL normally oriented with respect to the local ESL surface is used to approximate near cortical sources. The distance of positive and negative charge of each charge pair is 1 mm.

Both EDL and ECL consist of construction of an ESL (dipole or charge) in a volume conductor which simulates the head, so that the potentials generated by ESL would take the values measured on the scalp surface, i.e.

$$\sum_{j=0}^{N-1} u_i G(S, A_j) = \Phi(A_j)$$

where $\Phi(A_j) \ (j=1, 2, \cdots, M)$ are the electrical potentials on
the scalp of human brain produced by actual neural electric sources or tested by real experiment, $M$ is the number of electrodes, $N$ is the number of discrete equivalent layer sources and $u_i$ is the strength of a discrete equivalent source, and $G(S_i,A_j)$, $(i=0,1,\cdots, N-1; \ j=1,2,\cdots, M)$ is an element of the transfer matrix $G$ for a source located at $S_i$ to an electrode at $A_j$, which is determined by the source type such as a dipole or a charge and the volume conductor model. The $u_i$ is obtained by singular value decomposition (SVD) or other regularized inverse, then the potential outside the equivalent layer produced by ESL is assumed to be approximately the same as the actual potential produced by actual neural sources which are located inside the cortical layer\[2\]. In this way, EDL or ECL can be utilized as an intermediate step to get the desired epicortical potential which is of higher spatial resolution than that of the scalp surface potential\[4\].

In the following simulations and IOR experiment test, 128 electrodes are used and discrete equivalent layer sources $N$ is 2674. That means 2674 radial dipoles located on ESL for EDL Model and 2674 charge pairs located on ESL for ECL. Transfer matrix $G$ is calculated by the boundary element method (BEM) for the realistic 3-layer head model\[7\]–\[9\]. The middle of the line from the left ear to the right ear is defined as the origin of this realistic head model, the axis directing from the origin to the nasion is defined as $+x$, the axis directing from the origin to the left ear is defined as $+y$, and $+z$ axis is defined as the axis directing from the origin to the vertex.

3. Simulations

3.1 Charge Source

In these simulations, 4 or 6 charges are situated under the ESL to simulate the active neuro sources. For the simulation of 4 charges, each two of them are put nearby with distance of 1 mm, which looks like one radical dipole. They are $-0.5$, $0.5$, $-0.5$ and $0.5$, placed in positions $(10.0, -15.0, 43.0)$, $(10.4021, -15.3016, 43.8645)$, $(15.0, 18.0, 35.0)$ and $(15.3561, 18.4274, 35.831)$, respectively. In the simulation of 6 charges, they are $-0.5$, $0.5$, $-0.5$, $0.5$, $-0.5$, $0.5$, $-0.5$, $0.5$, placed in positions $(0.0, -11.0, 46.0)$, $(0.0, -11.8619, 46.507)$, $(0.0, 11.0, 46.0)$, $(0.0, 11.8619, 46.507)$, $(30.0, 0.0, 37.0)$ and $(30.7682, 0.0, 37.6402)$, respectively. They are 3 pairs of charge source and with almost radical direction to cortical surface. Then the potential $\phi$ of the scalp is calculated by BEM. According the method introduced in the above section, the potential $u_i$ on ESL is obtained by using both EDL and ECL model, respectively.

3.2 Dipole Source

Here, neuro activity is simulated by 2 or 3 near dipoles.

Fig. 1. 3D Maps of scalp potential, EDL and ECL for both charge source and dipole source: (a) maps of scalp potential, EDL and ECL of 4 charges source, (b) maps of scalp potential, EDL and ECL of 6 charges source, (c) maps of scalp potential, EDL and ECL of 2 dipoles source, and (d) maps of scalp potential, EDL and ECL of 3 dipoles source. The unit is mm.

The top-view of scalp potential, EDL, and ECL maps of 4 charges source are shown form left to right by Fig. 1 (a). In Fig. 1. Fig. 1 (b) shows the scalp potential, EDL, and ECL of 6 charges source, respectively. For the simulation of 4 or 6 charges, the maximum value and minimum value of the two color bars in each case are selected according to the maximum absolute value of EDL or ECL and labeled on top and bottom of the color bar, respectively. The real maximum value and minimum value of each EDL or ECL map are labeled on the right of its color bar, respectively.

When 4 charges are situated in the brain, the EDL value of $u_i$ changes from $-0.006$ to $0.002$ and the ECL value of $u_i$ changes from $-0.009$ to $0.003$. That means the EDL value varies in a wider range than the ECL value does. Similarly, for simulation of 6 charges, the EDL value of $u_i$ changes from $-0.003$ to $0.002$ and the ECL value of $u_i$ changes from $-0.006$ to $0.003$. Therefore, we get clearer source presentation by using ECL than by using EDL. Fig. 1 also shows that the 2 or 3 pairs charge source can be shown clearly in both EDL and ECL maps, while the charge source could not be distinguished by scalp potential maps.
under the human brain cortical layer. Two normal dipoles (0.6508, 0.0, 0.7593) and (0.0, 0.0, 1.0) are placed in positions (30.0, 0.0, 35.0) and (−0.0, 0.0, 55.0), respectively. Three normal dipoles (0.0, −0.8619, 0.507), (0.0, 0.8619, 0.507) and (−0.6402, 0.0, 0.7682) are placed in positions (0.0, −10.0, 47.0), (0.0, 10.0, 47.0), and (0.0, −30.0, 35.0), respectively. We obtain the potential $u_i$ on ESL by multiplying inverse matrix of $G$ calculated by SVD to the potentials of 128 electrodes.

Fig. 1 (c) and (d) show the scalp potentials and $u_i$ on ESL with 2 and 3 dipoles situated under the ESL. The $u_i$ on ESL is calculated from potentials of 128 electrodes on the scalp, while EDL and ECL model are used respectively. For 2 or 3 dipoles simulation, the maximum value and minimum value of the two color bar in each row are labeled on the bottom of the color bar and are selected according the max absolute potential of EDL or ECL. The real maximum value and minimum value of EDL are labeled on the right of the color bar near each EDL map. The real maximum value and minimum value of ECL are also labeled on the right of the color bar near each ECL map.

Fig. 1 (c) and (d) show that the dipole source could not be distinguished by scalp potential while both EDL and ECL images could distinguish dipole sources well. While 2 dipoles are placed in the brain, the EDL value of $u_i$ changes from −0.01 to 0.03 and the ECL value of $u_i$ changes from −0.02 to 0.05. That means the EDL value varies a wider range than the ECL value does. Further, for simulation with 3 dipoles, the EDL value of $u_i$ changes from −0.011 to 0.012 and the ECL value of $u_i$ changes from −0.019 to 0.024. Therefore, we got clearer source presentation by ECL than by EDL. The 2 or 3 dipole sources of ECL map are clearer than those of EDL map because the ECL value varies a wider range than the ECL value does.

4. Real Data Test

4.1 IOR Experiment

The phenomenon of IOR was discovered by Posner in 1984, which means subjects are slower to respond to targets presented at the cued location than to targets presented at uncued locations[10]. Thereafter, the neural and psychological mechanisms of IOR have been a popular subject of much controversy and debate. With empirical supports, some researchers suggested that IOR is a bias of attention. Others, however, have proposed that IOR is the activation of the oculomotor system. Recently, some evidences suggested that both attention and motor systems might be involved in the generation of IOR[11].

We adopted the modified classical experiment paradigm of inhibition of return (IOR), designed by Posner[12][13], to acquire the ERP recordings. EEG was recorded with the 128-channel EGI system at sampling rate of 250 Hz, and vertex (Cz) was taken as the reference. Epochs contaminated with excessive eye movements, blinks, muscle artifacts, or amplifier blocking were manually removed prior to averaging, and recordings of 13 in 15 subjects were valid and averaged for further processing. In this paper, ERP data used is the result of left cue-location and left target- location. Each epoch, which was 1.2 s long, started 200 ms before the onset of the target and continued for 1000 ms after the onset of the target.

Supposing the activations elicited by cue areseparated to three stages: the early stage (110 ms–240 ms), the middle stage (240 ms–350 ms), and the later stage (350 ms–650 ms). The focus of our experiments is the ERP of the early stage. The earliest component C1 primarily distributes on right parietal cortex. Component of early P1, of which the latent period is 144 ms, mainly locates on contralateral temporal occipital area, while component of later P1, of which the latent period is 170 ms, distributes on homolateral temporal occipital area. Early Nc2 (eNc2) is the second negative compound wave and locates on contralateral temporal cortex. Accordingly, we select four key time points as most typical instances and they are 120 ms, 144 ms, 176 ms, and 228 ms.

4.2 Results of ESL

3D topological ERP maps of left view field of the four time points are shown in Fig. 2. The back-view and top-view of ERP maps for each time point are shown in Fig. 2 (a). The unit of the scalp voltage is $\mu$V. Fig. 2 (b) and (c) show the back-view and top-view of EDL and ECL, respectively, which are calculated from the 128 averaged potentials of ERP of each time point and with the 3-layer realistic head model. The maximum value on top of the color bar and the minimum value on the bottom of the color bar in each ERP, EDL or ECL map are the absolute value of the maximum positive value or the minimum negative value of ERP, EDL or ECL for each time point. While the real maximum and the minimum potential values of each ERP, EDL or ECL are signed on the right of its color bar near the top-view of ERP, EDL or ECL map.

From the figure, we can see that more localized source distributions on both EDL map and ECL map can be obtained than those on the scalp ERP map. Furthermore, we can see clearer source location on ECL than that on EDL for each ERP of four time points. Comparing the real maximum and the minimum values of EDL and ECL of the same time point, we find all the ECL values vary in a wider range than the EDL value does. Consequently, higher resolution source was obtained by ECL map than by EDL map. Especially, two sources were got on homo-lateral temporal occipital for late P1 by both the EDL and ECL map of 176 ms, however, only one source could be found on the scalp map of this time point.
5. Conclusions and Discussion

Both EDL and ECL belong to ESL imaging, which is an important high-resolution EEG imaging method. Studies show that the strength density of EDL is proportional to the surface potential produced by the actual sources inside the surface with outside conductivity being zero and the boundary condition equation being satisfied automatically. The strength density of ECL is the normal surface current density produced by the actual sources inside the surface with outside conductivity being infinite such that the boundary condition equation is satisfied automatically\cite{1}. In this paper, the ESL method was put forward to use on a 3-layer realistic head model. Both charge sources and dipole sources under the ESL was applied to compare the difference of EDL and ECL. Simulation results show that higher spatial resolution about the source location can be obtained by ECL than by EDL. The same conclusion is obtained by the further study on real IOR experiment comparison. Therefore, both simulation results and IOR experiment results show that we can get better source resolution using the ECL model than using the EDL model. In addition, our IOR ERP experiment shows that two separated sources are found on homo-lateral temporal-occipital by both the EDL and ECL map of 176 ms, however, only one source can be found on the scalp ERP map. The new finding may lead to a new explanation or discovery of the IOR mechanism.

References


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